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<b>13. ABSTRACT (Maximum 200 Words)</b> Real-time, wide band information storage and signal processing devices are critical to many military and commercial systems in order to perform complex functions such as secure communications, network routing, pattern recognition, electronic surveillance and tracking, database management, and tactical air reconnaissance. Optical coherent transient technology (also referred to as spectral holography) has the potential to perform real-time storage and signal processing at data rates far exceeding 10 <sup>6</sup> GHz, with storage/pattern densities on the order of a terabit per centimeter squared, and with data block sizes/time-bandwidth products well over 10000. The main objective of the grant was to support the research of two graduate students and augment the research of the parent grants F49620-93-1-0513 and F49620-97-1-0259. The augmented research under these grants included work on true-time delay regenerators, power induced time-shifts, chirped pulse programming of coherent transient true-time-delay devices, recall efficiencies in optically thick media (non-inverted), Coherent transient optical signal processing without brief pulses, Compensation for homogeneous dephasing, and modeling and characterization of gated systems.				
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**Final Report**  
**on**  
**Coherent Transient Processors and Materials**

**Grant Number**  
**F49620-95-1-0468**

**Submitted to:**  
**Dr. Alan E. Craig**  
**Air Force Office of Scientific Research/NE**  
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**By**  
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**For**  
**Department of Electrical Engineering, University of Washington**  
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**Covering 7/1/95 to 6/30/98**



## Objectives

The main objective of the grant was to support the research of two graduate students and augment the research of the parent grants F49620-93-1-0513 and F49620-97-1-0259. The AASERT supported Kristian D. Merkel and Molly J. Byrne through 6/15/97 and then supported Carrie C. Cornish and Molly J. Byrne. All three students are graduate students of the Department of Electrical Engineering at the University of Washington. After Prof. Babbitt's move to Montana State University, Molly and Carrie continued pursuing their degrees from University of Washington until Prof. Leung Tsang, while Prof. Babbitt remained their technical advisor. They worked with Prof. Tsang on theoretical aspects of their work and did their experimental work in Prof. Babbitt's laboratory at Montana State University.

## Summary

Kris' research plan included 1) experimental validation of theoretical predictions of coherent transient output signal size and fidelity loss due to non-linear effects, 2) demonstration of coherent transient true-time delay with chirped programming pulses, and 3) demonstration of a high performance triple product correlator in a solid with large time-bandwidth products. This work included material exploration of two-level systems capable of carrying out the validation experiments and demonstration of the correlation and convolution processing with optical coherent transients. Kris received his Ph.D. from the University of Washington in June 1998.

Molly's research plan included 1) application of the theory of electron tunneling to the study of electron transfer in molecules and crystals, 2) development and characterization of gateable coherent transient materials. Molly is continuing this research towards her Ph.D. from the University of Washington.

Carrie's research plan included 1) Study of the non-linear effects in coherent transient storage and processing 2) High efficiency of coherent transient signal in optically thick and inverted media, and 3) Study of the energy sources of optical coherent transient signals. Carrie is continuing this research towards her Ph.D. from the University of Washington.

## Achievements/New Findings

(also reported under parent grants F49620-93-1-0513 and F49620-97-1-0259)

### *Optical Coherent Transient true-time delay regenerators*

The paper "Optical coherent transient true-time delay regenerator" describes the application of spatial-spectral holography to true-time delay processing for phased array radar transmitters and receivers. Coherent transient true-time delays have the ability to simultaneously, and continuously process several hundred delays over a broad bandwidth with fine temporal resolution. This will enable wide angle ( $> 45$  degrees) beamsteering of wide-bandwidth ( $> 10\text{GHz}$ ) for multi-element ( $> 1000$ ) arrays. Multicasting and

simultaneous delay and temporal processing capabilities are additional features.

### ***Photon Echo Data Recall Efficiencies***

The most significant result is that theoretical prediction that data recall efficiencies much greater than unity are achievable in optically thick inverted media while maintaining high fidelity in the recall of data signals. Enhanced efficiencies are critical to making coherent transient devices practicable. These results are significant in that they may lead to highly efficiency, large time-bandwidth product, broad band processing, routing, and storage devices. The results were in the paper "Efficient waveform recall in absorbing media," presented by C. S. Cornish at the 1998 Conference on Lasers and Electro-Optics and reported in the journal publication by M. Azadeh, C. Sjaarda Cornish, W. R. Babbitt, and L. Tsang, "Efficient photon echoes in optically thick media," in Physical Review A 57, 4662-8. We have now demonstrated echo efficiencies of 50% in barium vapor and expect further refinements of our experiment to yield echo efficiencies exceeding unity. Further research in this area will be done in doped crystal, specifically Tm: YAG crystals. Unity efficiency would mean the devices can be inserted with minimal insertion loss and possible gain, allowing for cascading devices and achieving feedback and adaptation.

### ***Power induced Time-shift of coherent transient output signals***

It was found that there is a shift in the timing of the output signals of coherent transient true-time-delay regenerators. A paper has been prepared for publication on the role of nonlinearities in the material excitation of the delay timing. It was found that the delayed output of a coherent transient true-time-delay regenerator was shifted as a function of the strength of the input pulses. It was found that as the pulse area of the programming pulses or read pulse approached  $\pi/2$ , significant shift occurred in the delayed output. The sign of the temporal shift depended on which pulse was being varied and it was found that this shift was related to whether the information about the coherent transient output of interest was being transferred from a population to a coherence or from a coherence to a population. These shifts were analyzed experimentally, analytically, and through numerical simulation and are now well characterized. The maximum shift is about 10% of the duration of the programming pulses and should not significantly affect the operation of coherent transient true time delay. In addition, since the shifts are well understood, this information can be used to compensate the programming of true-time-delay regenerators. A manuscript is in preparation. The results have were presented by K. D. Merkel in the paper "Temporal dependence of coherent transient regenerated true-time-delays on intensity of applied pulses" at the 1998 Conference on Lasers and Electro-Optics. Further research on similar effects when programming with chirped pulses would be worth pursuing.

### ***Chirped pulse programming of coherent transient true-time-delay devices***

It was proposed and demonstrated that chirped reference pulses can be used in the programming of optical coherent transient true-time delays. Coherent transient true-time delay devices have the ability to simultaneously, and continuously process several hundred delays over a broad bandwidth with fine temporal resolution. Such devices will find application in phased array antennas and will enable wide angle ( $> 45$  degrees) beamsteering of wide-bandwidth ( $> 10\text{GHz}$ ) for multi-element ( $> 1000$ ) arrays. Multicasting and simultaneous delay and temporal processing capabilities are additional features. Chirped pulses an order of magnitude longer than the delay resolution desired can be used to introduce precise delays. Varying the temporal separation between the chirped reference pulses or more significantly by introducing a frequency shift of one or both of the chirped reference pulses can program delays. The use of frequency shift programming enables fine delay resolution that is controlled simply with a frequency-shifting device. The change in delay is proportional to the frequency shift (it equals the frequency shift divided by the chirp rate). This work was documented in the paper by K. D. Merkel and W. R. Babbitt, "Chirped-pulse programming of optical coherent transient true-time delays," *Optics Letters* 23, 528-30 (1998) and presented by K. D. Merkel in the paper "Chirped Pulse Programming of Spatial-Spectral Holographic True-Time Delays" at the The Eighth Annual DARPA Symposium on Photonic Systems for Antenna Applications in Monterey, CA.

### ***Echoes in an Inverted Media***

As reported in the final report of F49620-93-1-0513, the enhanced efficiencies that are achievable in inverted media has been shown via computer simulation. The most significant result is that data recall efficiencies much greater than unity are achievable in optically thick inverted media while maintaining high fidelity. Updated results of this work were presented by W. R. Babbitt in the talk "Coherent Transients in Inverted Media," at the Frontiers of Applications of Photospectral Holeburning Workshop. Experiments to verify these results were attempted in barium vapor. However, vapor samples are not suitable for this demonstration due to the long coherence lifetime compared to the excited population decay. Schemes for demonstrating this in doped crystal are being explored.

### ***Coherent transient optical signal processing without brief pulses***

The paper "Compensation for homogeneous dephasing in coherent transient optical memories and processors" describe a technique that eliminates the need for intense brief pulses in the programming of routers and processors. In these devices, previous programming was accomplished with a pattern pulse and an intense brief pulse. Intense brief pulses are difficult to produce practically and thus hindered the implementation of optical coherent transient processors and routers. It was demonstrated that these devices could be programmed instead with a pattern pulse and two chirped pulses of significantly lower intensity. Chirped laser pulses can be produced practically and thus this technique enhances

the prospects of achieving practical optical coherent transient devices.

### ***Compensation for homogeneous dephasing in coherent transient optical devices***

The paper "Compensation for homogeneous dephasing in coherent transient optical memories and processors" describes a technique for increasing the time-bandwidth product or storage capacity of coherent transient devices by up to an order of magnitude. By applying a ramp to the programming pulses in either memory or processing optical coherent transient devices, the effects of homogeneous decay can be compensated for and faithful correlations and recall can be accomplished with much higher time-bandwidth products than would be achievable without the technique. Practical considerations limit the increase to about a factor of 10. The technique is a practical means for implementation of coherent transient routers, processors, and memories with enhanced performance.

### **Personnel**

#### ***Personnel Supported:***

Molly J. Byrne, Graduate Research Assistant  
Kristian D. Merkel, Graduate Research Assistant (before 6/15/97)  
Carrie S. Cornish, Graduate Research Assistant (after 6/16/97)

#### ***Degrees awarded:***

Kristian D. Merkel, Ph.D. in Electrical Engineering, June 1998

### **Publications (also reported under parent grants F49620-93-1-0513 and F49620-97-1-0259).**

#### ***Peer-reviewed journal publications:***

K.D. Merkel and W.R. Babbitt, "Optical coherent transient header/data isolation technique," *Optics Letters* 21, 71-73 (1996).

K.D. Merkel and W.R. Babbitt, "Coherent transient optical signal processing without brief pulses," *Appl. Optics*, 35, 278-285 (1996).

K. D. Merkel and W.R. Babbitt, "Compensation for homogeneous dephasing in coherent transient optical memories and processors," *Optics Comm.* 128, 136-144 (1996).

K. D. Merkel and W. R. Babbitt, "Optical coherent transient true-time delay regenerator," *Optics Letters* 21, 1102-1104 (1996).

K. D. Merkel and W. R. Babbitt, "Chirped-pulse programming of optical coherent transient true-time delays," *Optics Letters* 23, 528-30 (1998).

M. Azadeh, C. Sjaarda Cornish, W. R. Babbitt, and L. Tsang, "Efficient photon echoes in optically thick media," *Physical Review A* 57, 4662-8 (1998).

***Reviewed conference publications:***

K. D. Merkel and W.R. Babbitt, "Coherent transient optical signal processing without brief reference pulses," in Photonics in Computing II, Leo J. Irakliotis, Editor, 117-126 (1995), Fort Collins, Co., June 6-9, 1995.

K. D. Merkel and W. R. Babbitt, "Homogeneous dephasing compensation in coherent transient optical memories and processors," in Conference on Lasers and Electro-Optics, Vol. 9, 1996 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1996) pp 197-198. Anaheim, Ca., June 2-7, 1996.

K. D. Merkel and W. R. Babbitt, "A coherent transient optical true-time delay generator for phased array radar," The 5th International Meeting on Hole Burning and Related Spectroscopies (HBRs '96), Brainerd, Minn., September 13-17, 1996.

K. D. Merkel and W. R. Babbitt, "Optical coherent transient header/data isolation technique," The 5th International Meeting on Hole Burning and Related Spectroscopies (HBRs '96), Brainerd, Minn., September 13-17, 1996.

K. D. Merkel and W. R. Babbitt, "Chirped Pulse Programming of Spatial-Spectral Holographic True-Time Delays," The Eighth Annual DARPA Symposium on Photonic Systems for Antenna Applications, January 14-16, 1998, DTIC# ADB 223444 PAA.

K. D. Merkel and W. R. Babbitt, "Temporal dependence of coherent transient regenerated true-time-delays on intensity of applied pulses," in Conference on Lasers and Electro-Optics, Vol. 6, 1998 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1998) pp 171. San Francisco, Ca., May 3-8, 1998.

C. S. Cornish, M. Azadeh, W. R. Babbitt, and L. Tsang "Efficient waveform recall in absorbing media," in Conference on Lasers and Electro-Optics, Vol. 6, 1998 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1998) pp 214-5. San Francisco, May 3-8, 1998.

**Interactions/Transitions: (also reported under parent grant F49620-93-1-0513 and F49620-97-1-0259)**

**a. Participation/presentations at meetings, conferences, etc.**

***Invited Conference Presentations:***

K. D. Merkel and W. R. Babbitt† († Invited Speaker), "Coherent transient optical memories and processors with homogeneous dephasing compensation," The 5th Intl Meeting on Hole Burning and Related Spectroscopies (HBRs '96), Brainerd, MN, September 13-17, 1996.

W. R. Babbitt, "Spatial-Spectral Holographic Memories, Processor, and Routers," in *Optics in Computing*, Vol. 8, 1997 OSA Technical Digest Series (OSA, Washington DC, 1997), pp172-174, Incline Village, NV, March 16-21, 1997.



W. R. Babbitt, "Spatial-Spectral Holographic Routing and Processing Devices", in Conference on Lasers and Electro-Optics, Vol.11, 1997 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1997) pp 213. Baltimore, MD, May 18-23, 1997.

***Other Conference Presentations:***

K. D. Merkel and W. R. Babbitt, "A coherent transient optical true-time delay generator for phased array radar," The 5th International Meeting on Hole Burning and Related Spectroscopies (HBRS '96), Brainerd, Minn., September 13-17, 1996.

K. D. Merkel and W. R. Babbitt, "Optical coherent transient header/data isolation technique," Poster, The 5th International Meeting on Hole Burning and Related Spectroscopies (HBRS '96), Brainerd, Minn., September 13-17, 1996.

C. S. Cornish, M. Azadeh, W.R. Babbitt, and L. Tsang, "Efficient waveform recall in absorbing media," Proceedings of the SPIE, Advanced Optical Memories and Interfaces to Computer Storage, San Diego, CA, July 22-24, 1998, Vol. 3468, paper 3468-26 (1998).

***Workshop attended by both Molly and Kris:***

"PSHB System Analysis," at Material Requirements for Persistent Spectral Hole Burning and Time-Domain Optical Storage and Processing, August 3-4, 1995, Bozeman, MT.

***Web Sites and Listserves Maintained***

Persistent Spectral Holeburning Web Page and Bulletin Board listserve:

Web site: <http://weber.u.washington.edu/~rbabbitt/pshb.html>

Listserve: [pshb@ee.washington.edu](mailto:pshb@ee.washington.edu)

***Collaborations***

A Twinning proposal was submitted that would allow for collaboration with I. Sildos of the Institute of Physics, Tartu, Estonia on the development of the neutron irradiated sapphire gated materials.

**New Discoveries, Inventions, and Patent Disclosures**

(also reported under parent grant F49620-93-1-0513)

***Inventions:***

W. R. Babbitt and K. D. Merkel, "Coherent Transient True-Time Delay Generation Technique", Invention Disclosure filed 2/7/96.

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